A 21st Century Approach to Reliability Program Overview

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Agenda

- Monday
  - 12:00 Lunch, Welcome - Dean Abernathy
  - 1:00 Perspectives - Kitt Reinhardt
  - 1:30 Overview - Mark Law
  - 2:15 AFRL Devices - Via
  - 2:35 Tester Overview - Cheney
  - 3:00 Break
  - 3:30 Materials Characterization Abernathy / Holzworth
  - 4:30-6:00 Student Posters
  - 6:30 Dinner - Napolitano's
- Tuesday
  - 8:00 Continental Breakfast
  - 8:30 Electrical Measurements / Strain - Nishida / Thompson
  - 9:30 Noise Modeling and Measurements, Bosman
  - 10:00 Device Simulation, Law
  - 11:00 Summary
  - 11:15 Caucus
  - 12:00 Lunch / Feedback / Individual Discussions

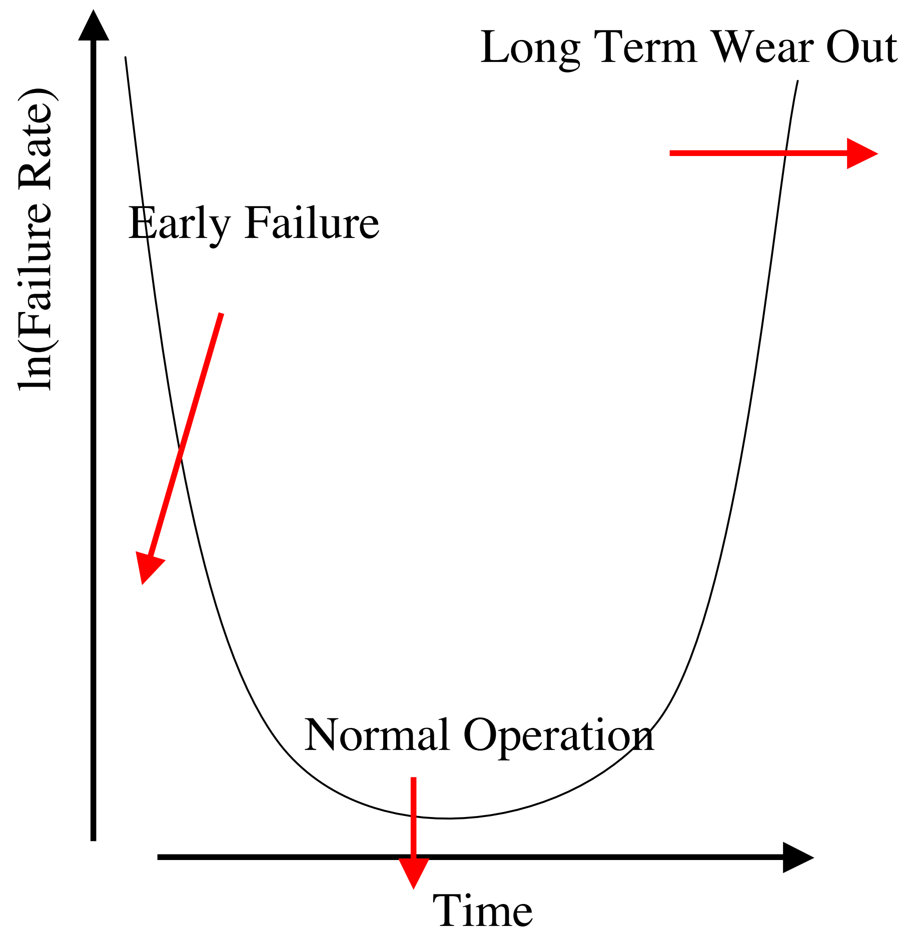
Presentations at:
www.reliability.ece.ufl.edu

Outline

- Background
- Goals and Objectives
- Status
- Research Highlights

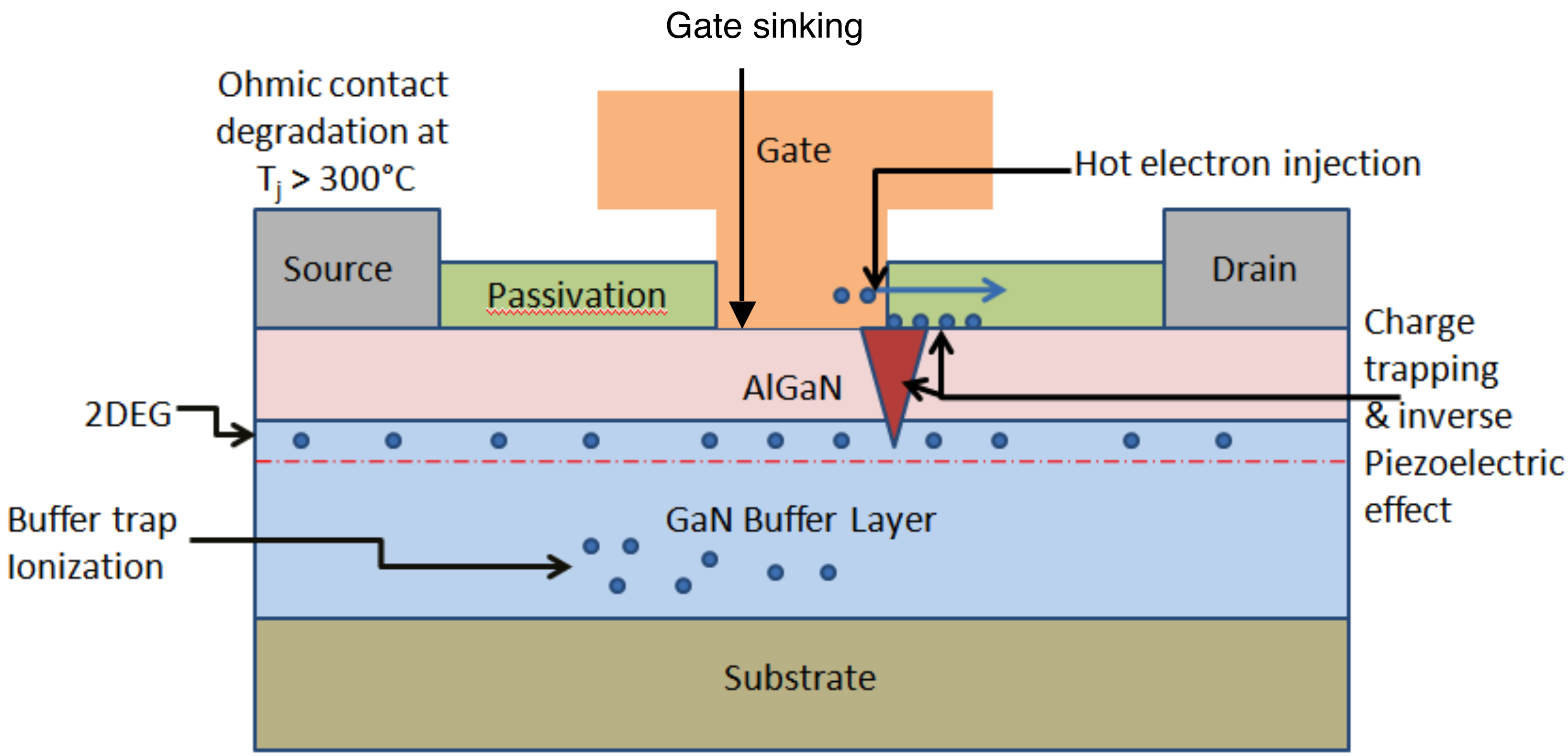
Electronic Lifetime - Bath Tub Curve

- Industry Objectives
  - Reduce Early Failure
  - Reduce Random Failure
  - Length time to Wear Out
- MURI Research
  - Develop early detection tools Canary in the coal mine
  - Provide Understanding of Failure to reduce random components
  - Identify causes of long term wear
  - Develop better accelerated testing



Push the curve in the red directions

Degradation of GaN HEMT's

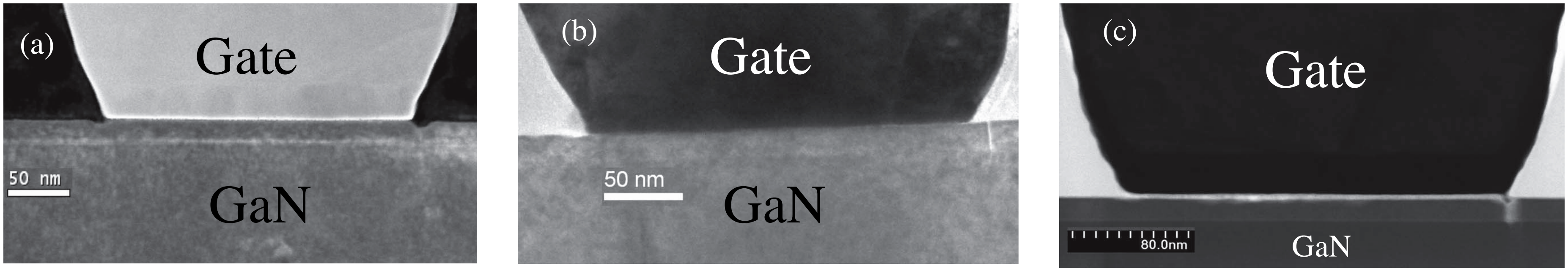


Objectives:

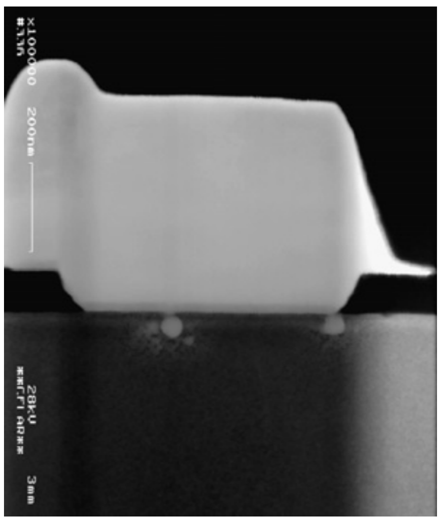
Develop a testing methodology for failure modes

Develop physical understanding of the failure modes

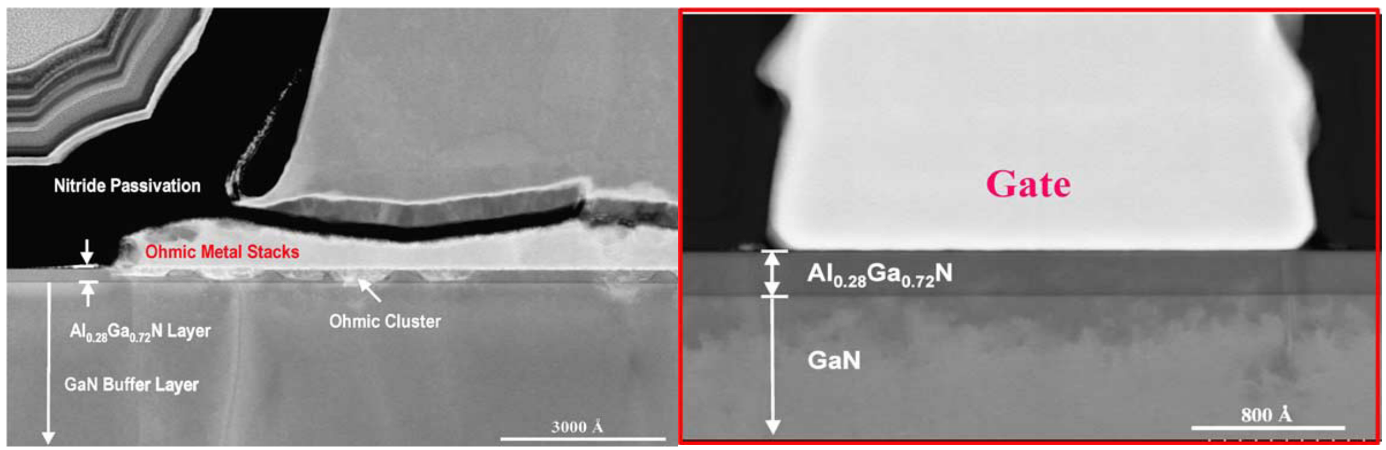
GaN X - Sections of Structural Failure Mechanisms



Chowdhury U et al. TEM Observation of Crack- and Pit-Shaped Defects in Electrically Degraded GaN HEMTs. IEEE Electron Dev Lett 2008; 29: 1098-1100.



Burgaud P et al. Preliminary reliability assessment and failure physical analysis on AlGaN/GaN HEMTs COTS. Microelectron Reliab 2007; 47: 1653-7.



Bright A N et al. Correlation of contact resisitance with microstructure for Au/Ni/Al/Ti/AlGaN/GaN ohmic contacts using transmission electron microscopy. J App Phy; 89: 3143-50.

Research Thrusts - Support Thrusts

- T1 Fabrication - Pearton
  - Several Industrial Partners
  - AFRL Base Line Devices
  - Experimental Fab Support for Test Structures
- T2 - Statistical Support - Pearton
  - Collaborate w/ Intel Reliability Team
  - Work with best Si techniques / approaches

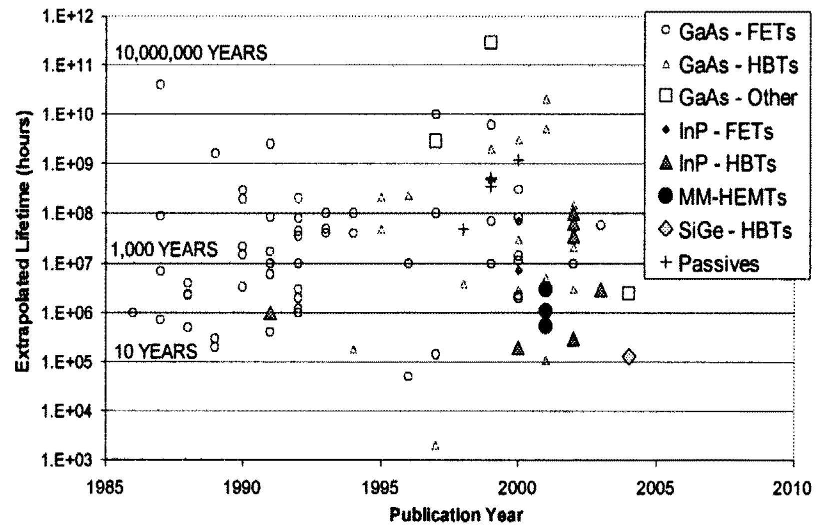


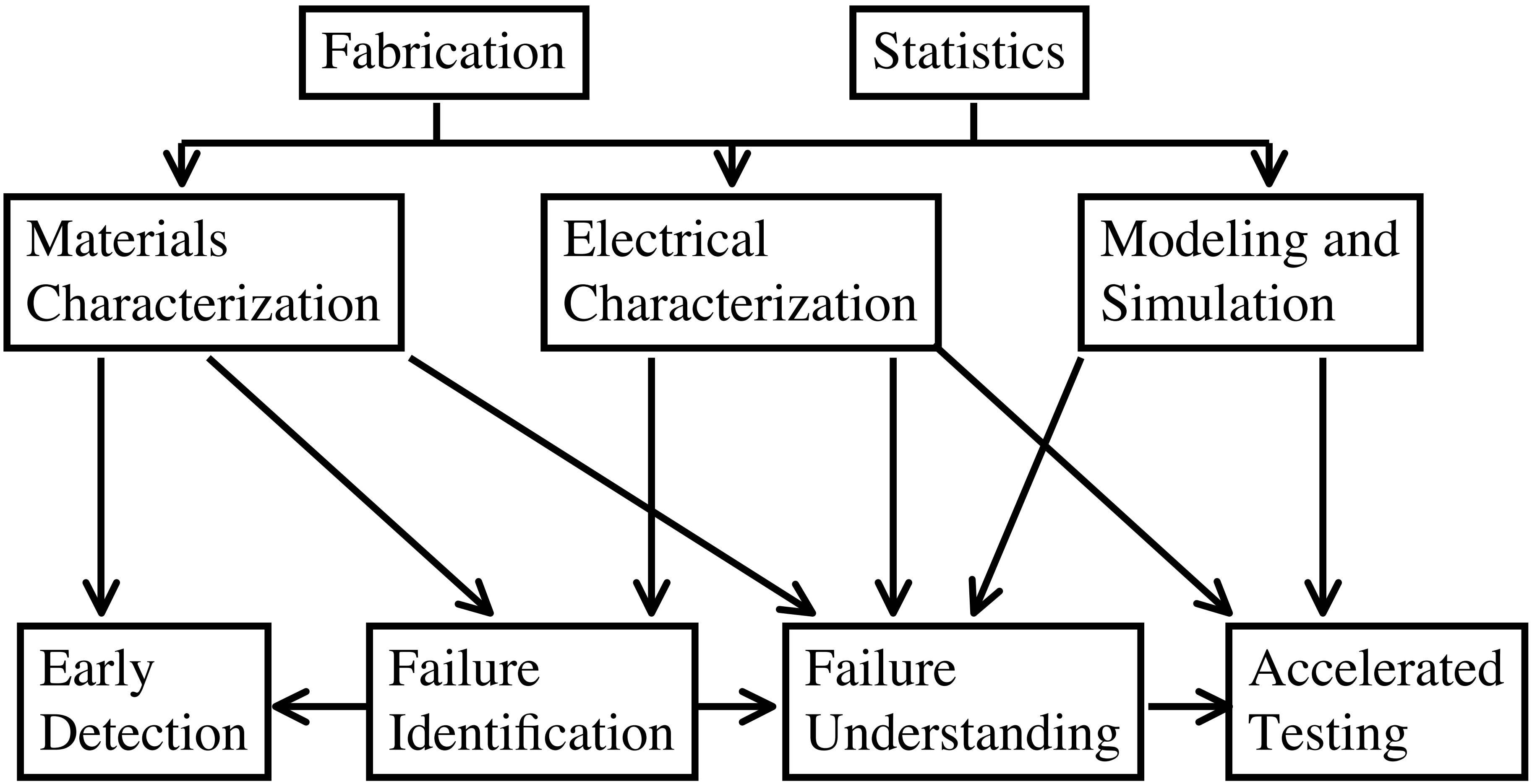
FIGURE 1. REPORTED OPERATING LIFETIMES FOR VARIOUS COMPOUND SEMICONDUCTORS OVER THE 19 YEAR HISTORY OF THE ROCS WORKSHOP[1]

Roesch, 2006

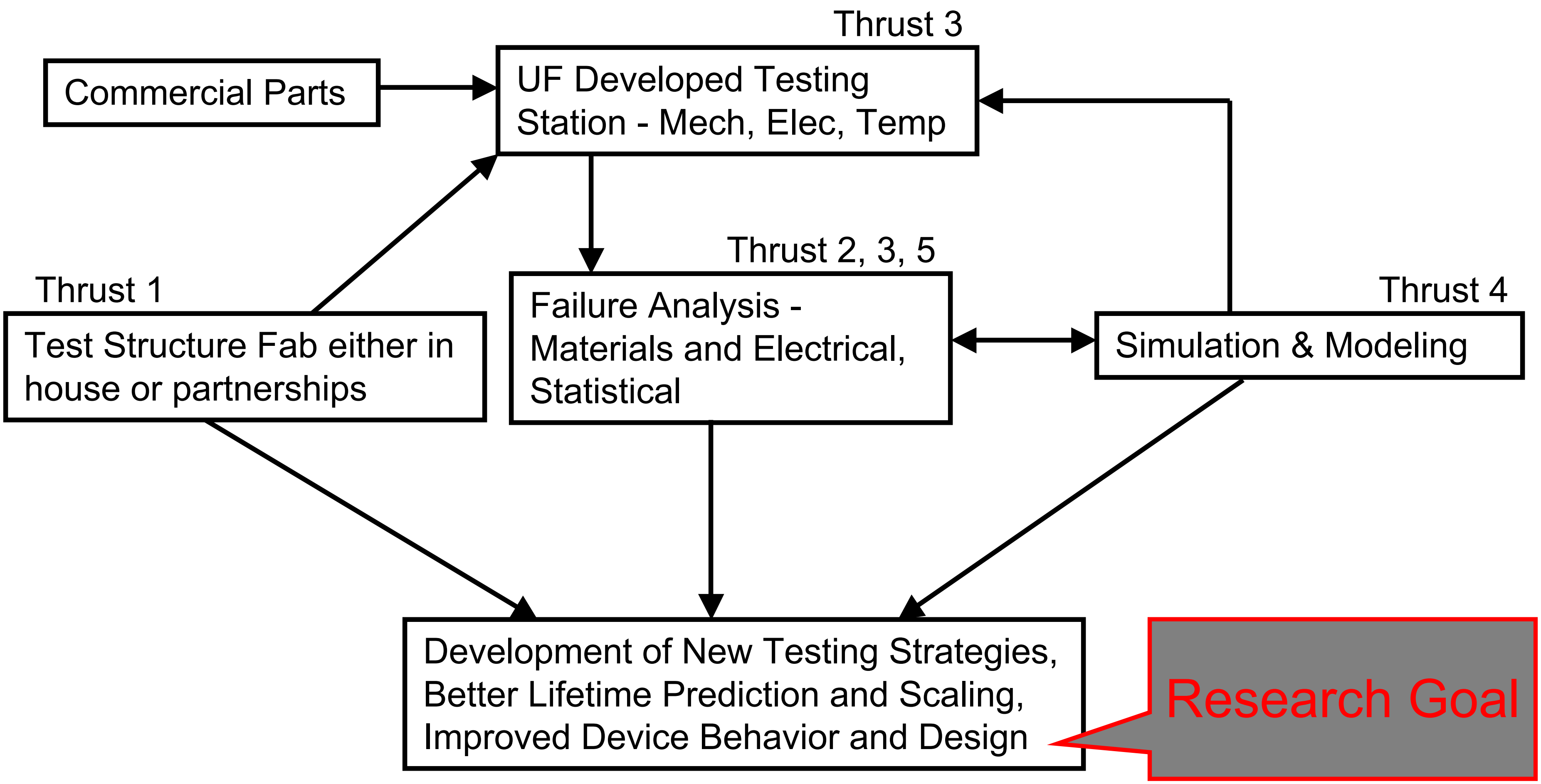
Research Thrusts - Primary

- Thrust 2 - Materials Characterization - Abernathy
  - Optical Techniques
  - Electron Microscopy
  - LEAP
- Thrust 3 - Electrical Characterization - Nishida
  - Burn-in and Tester Development
  - Mechanical Stress
  - Noise
- Thrust 4 - Modeling - Law
  - TCAD Extended Approaches
  - Noise
  - Mechanical Stress

Thrust to Problem Relationships



Research Work Plan



Precompetitive Engineering Scientific Research Focus

- Scientific Understanding of Materials Properties
- Understanding of Electrical Signatures
- Modeling / Simulation of Failure

- Black's Equation Empirically Captured Aluminum Electromigration in 1969
- Subsequent work on
  - Characterization of field, current density, temperature dependence
  - Characterization of mechanical stress
  - Characterization of grain size diffusion along grain boundaries
  - Characterization of etch effects related to grain size
  - Full 3-Dimensional Grain Models

Recent Papers in 2008 and 2009 - 40 years of science based pubs

Collaborations with Industry

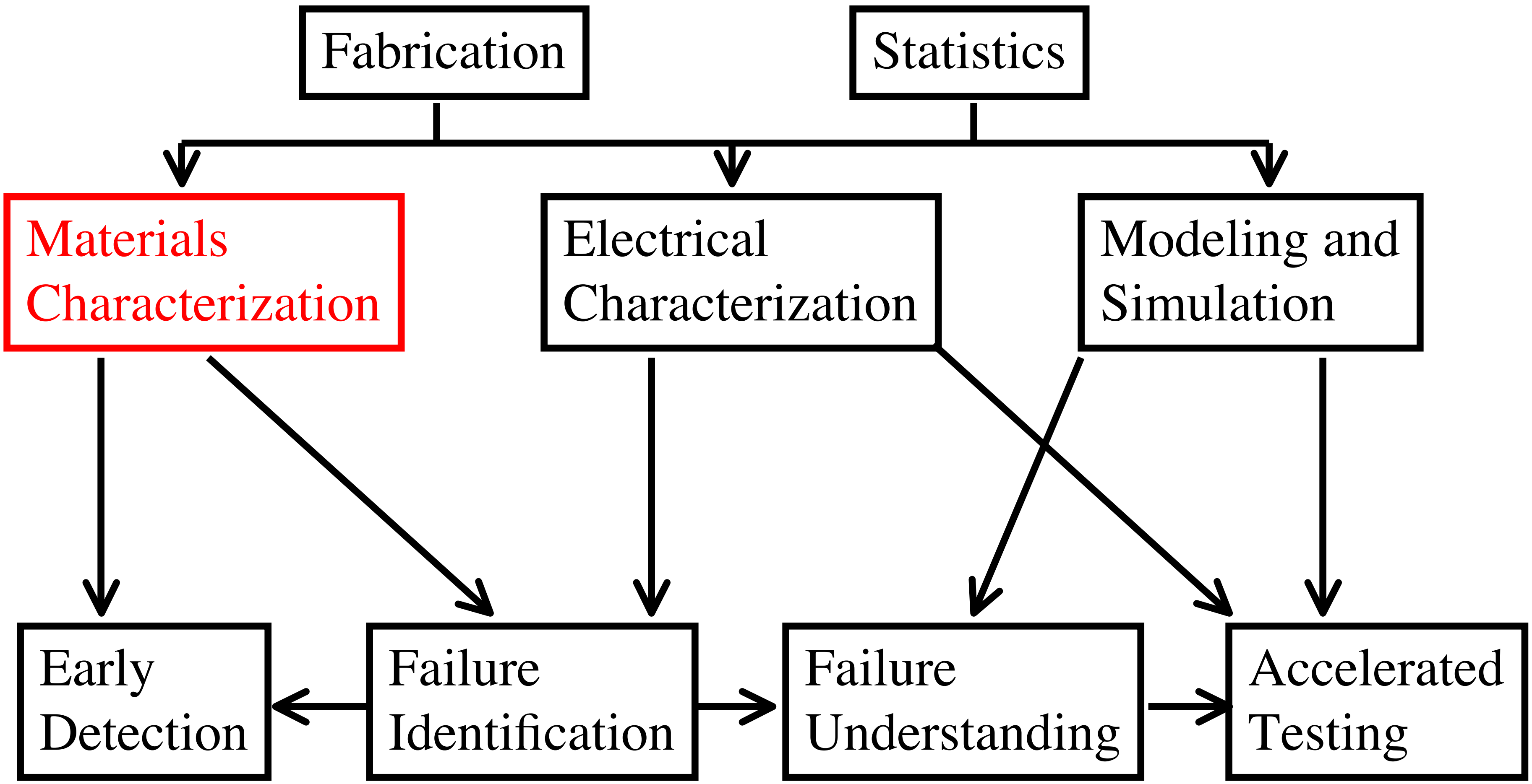
- **RFMD**
  - 77 stressed devices attached to RF boards
    *Survived 1000 hour RFMD lifetime test in October 2008
  - 2500 unstressed devices
- **Nitronex**
  - 60 unstressed devices
- **WIN Semiconductor**
  - 20 unstressed devices
  - 8 stressed devices
  - 15 TLM strips
- **Northrop Grumman**
  - 3 unstressed devices

ITAR / Export Control

- Controlled Room in NRF
- Devices kept in locked room and locked cabinet
- Sign in / sign out for experimentation
- ITAR Training Provided

- We can work with corporate devices
- Have controls in place

Materials Characterization Thrust



Cathodoluminescence (CL) system

FEI Nova NanoSEM (FEG source) with:
- EDAX Apollo silicon drift detector (TE cooled)
- Gatan MonoCL3+

FEI SEM arrived Sept 1st and is installed.
- Landing energy 50 V to 30 kV, continuously adjustable
- Resolution High-vacuum: <1.0 nm @ 15 kV, 1.6 nm @ 1 kV

EDAX installed EDS detector on Sept. 15th. Boron lowest element detected.

Gatan to install detector on Sept. 22nd, MonoCL3+ detector allows for spectrum mapping with 150 line/mm grating or high resolution spectrum at a spot with a 1200 line/mm, grating. Short working distance parabolic mirror allows for higher resolution.

Tool and facility optimized for highest resolution possible.

XPS/UPS Summary

Design experiment to determine changes in SiNx passivation during device operation/stressing

-MOCVD u-GaN/sapphire and AlGaN/GaN/sapphire

-5nm PECVD SiNx deposited on substrates (250°C, 60W) to ensure the Ga peak is visible.

Use 200°C anneal as a starting temperature and perform first anneals in the controlled environment of UHV. Temperature approximates device temperature under normal operation.

SiNx on u-GaN

Shift in VB of -0.4eV after vacuum anneal at 200°C. Ga-O portion of peak lost. No significant changes in Si 2p peak.

VB offset recovers to initial value after anneal in air at 200°C. Ga 3d peak recovered Ga-O portion. Peak positions and relative intensities are nearly identical to pre vacuum anneal values.

SiNx on HEMT

Shift in VBM of -0.9eV after vacuum anneal. No determined Ga-O bonding in the Ga 3d peak.

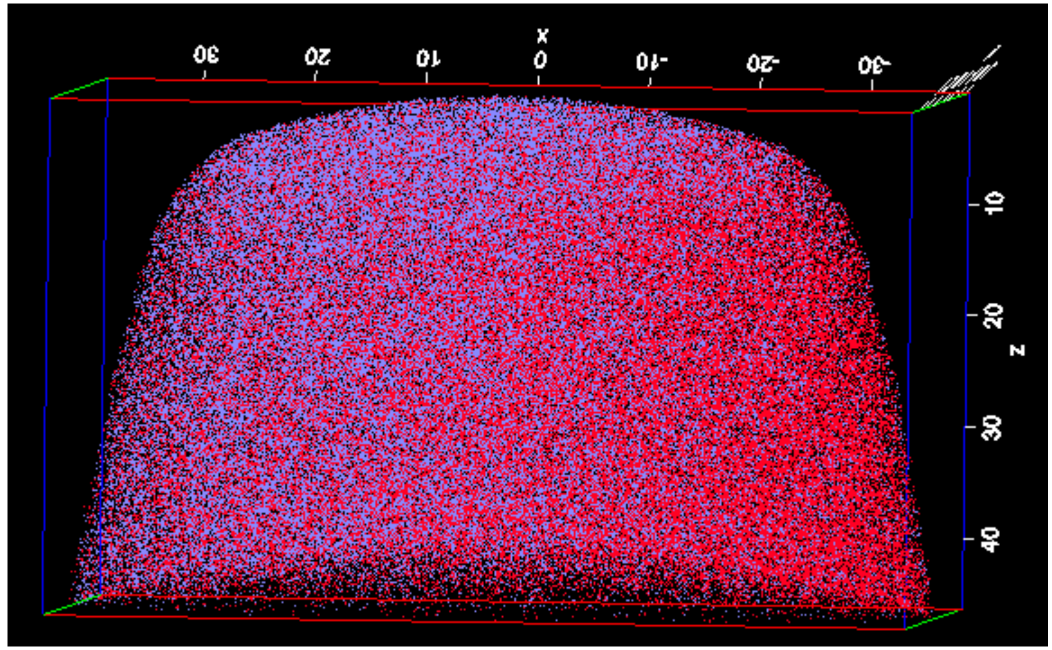
VB offset recovers to initial value after air anneal, similar to SiNx/u-GaN sample.

Different mechanism for the SiNx/u-GaN and SiNx/HEMT causing a VB shift.

Previous LEAP Analysis

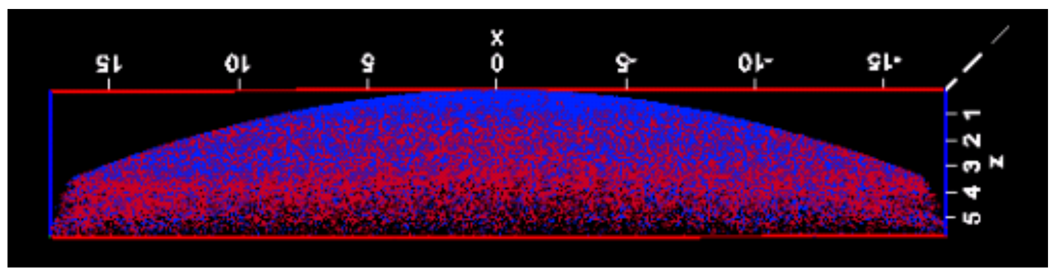
- First Ever Reported LEAP image from GaN

- LEAP reconstruction under gate (GaN layer)



Ga
N

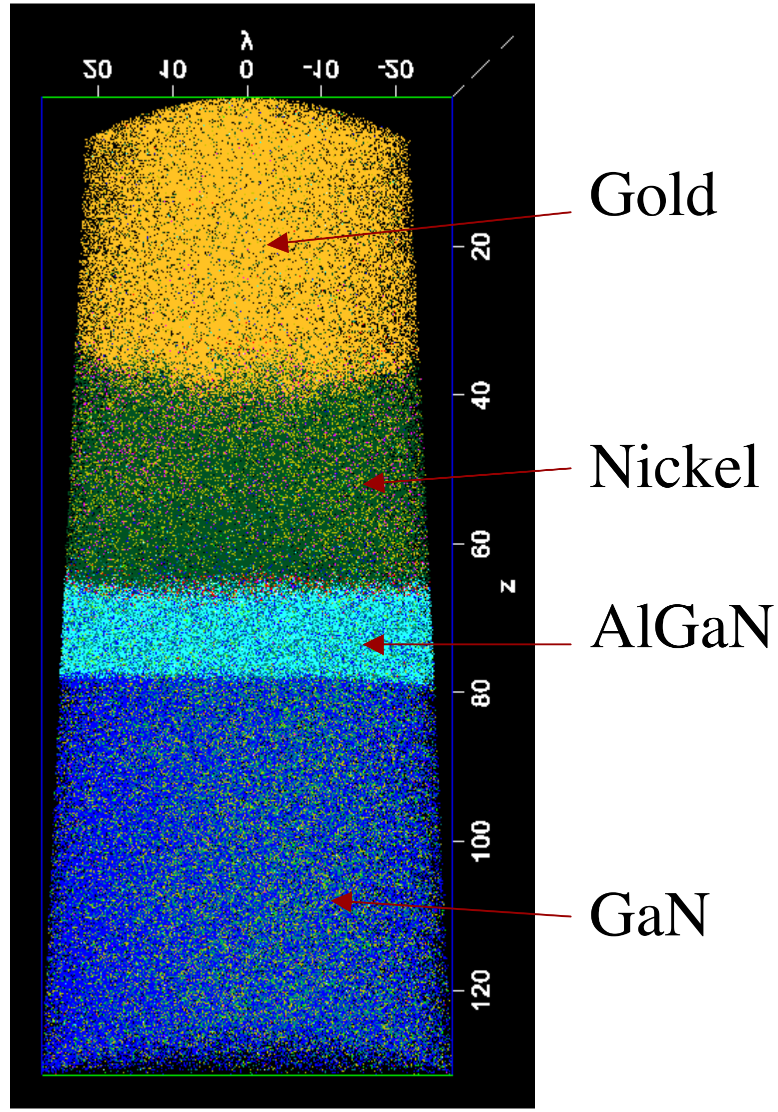
- LEAP reconstruction of part of the source ohmic contact stack



Ni
Ti

New LEAP Analysis

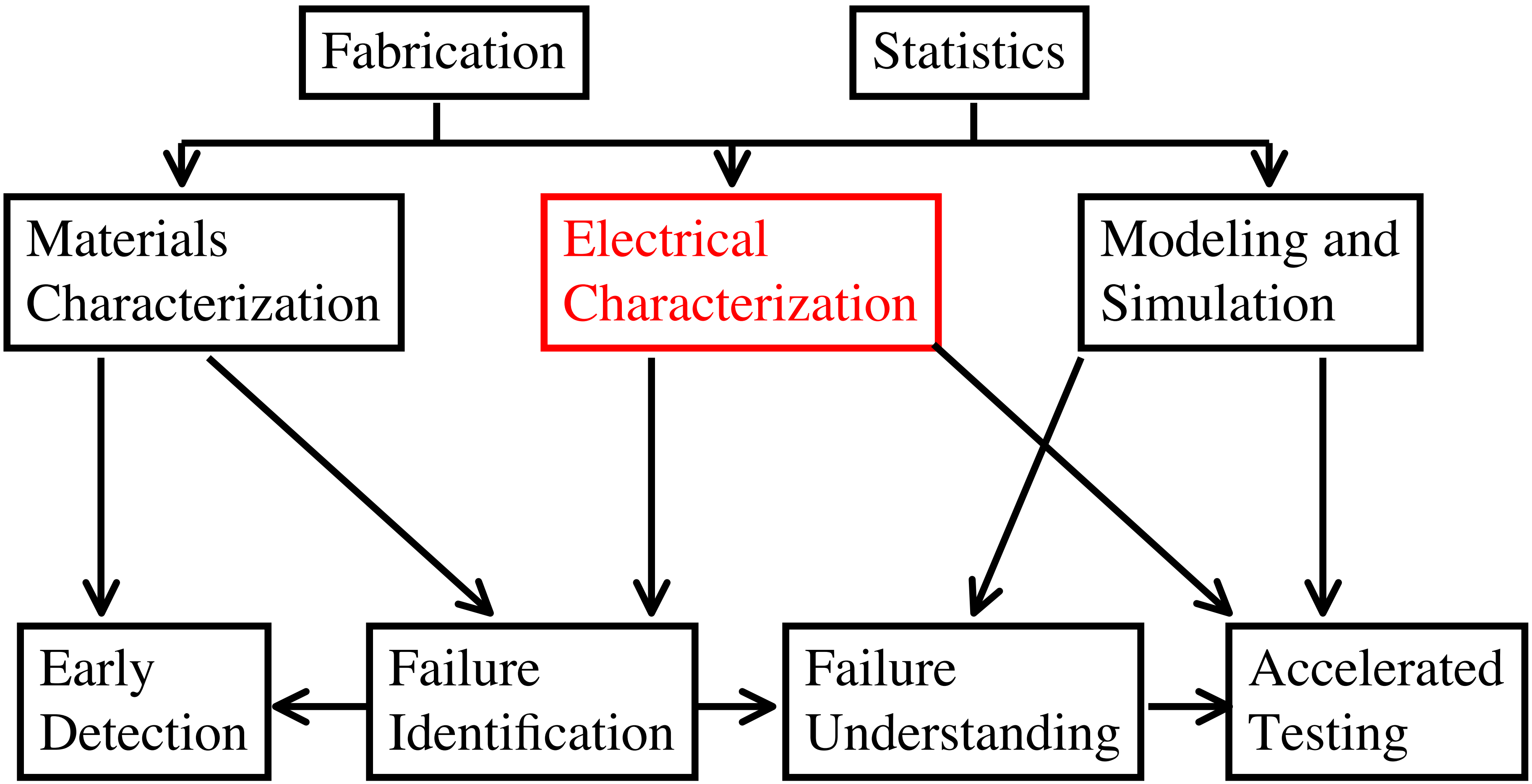
- Recently completed First Reported LEAP reconstruction of the entire gate stack.
- Reconstruction Features
  - Gate metal stack
  - Gate/Semiconductor interface
  - AlGaN/GaN interface
- Analysis
  - Interface curvatures
  - Interfacial layers
  - Concentration Profiles



Work in Progress / Future Research

- On going Work
  - Stress experiments on Nitronex epi-structure wafers
    - In-plane stresses will be applied to the wafers by bending them in quartz bending jigs.
    - This will replicate the stresses the HEMTs experience due to the inverse piezoelectric effect under high bias conditions.
      - Because the wafers will be mechanically bent, no electric field will be applied to the wafers and no orthogonal stress component will be examined.
      - This will characterization the importance of the electric field and vertical stress component to defect formation compared to the in-plane components.
      - A critical stress for defect formation will be established by performing experiments at different stress states.
      - Also, the effect of stress on the reactions between the epi-layers will be determined.
- Future Work
  - TEM and LEAP on devices
    - Produce a LEAP reconstruction of the Gate/SiN_x/AlGaN gate edge interface.
    - Produce TEM micrographs and LEAP reconstructions of stressed/failed devices.

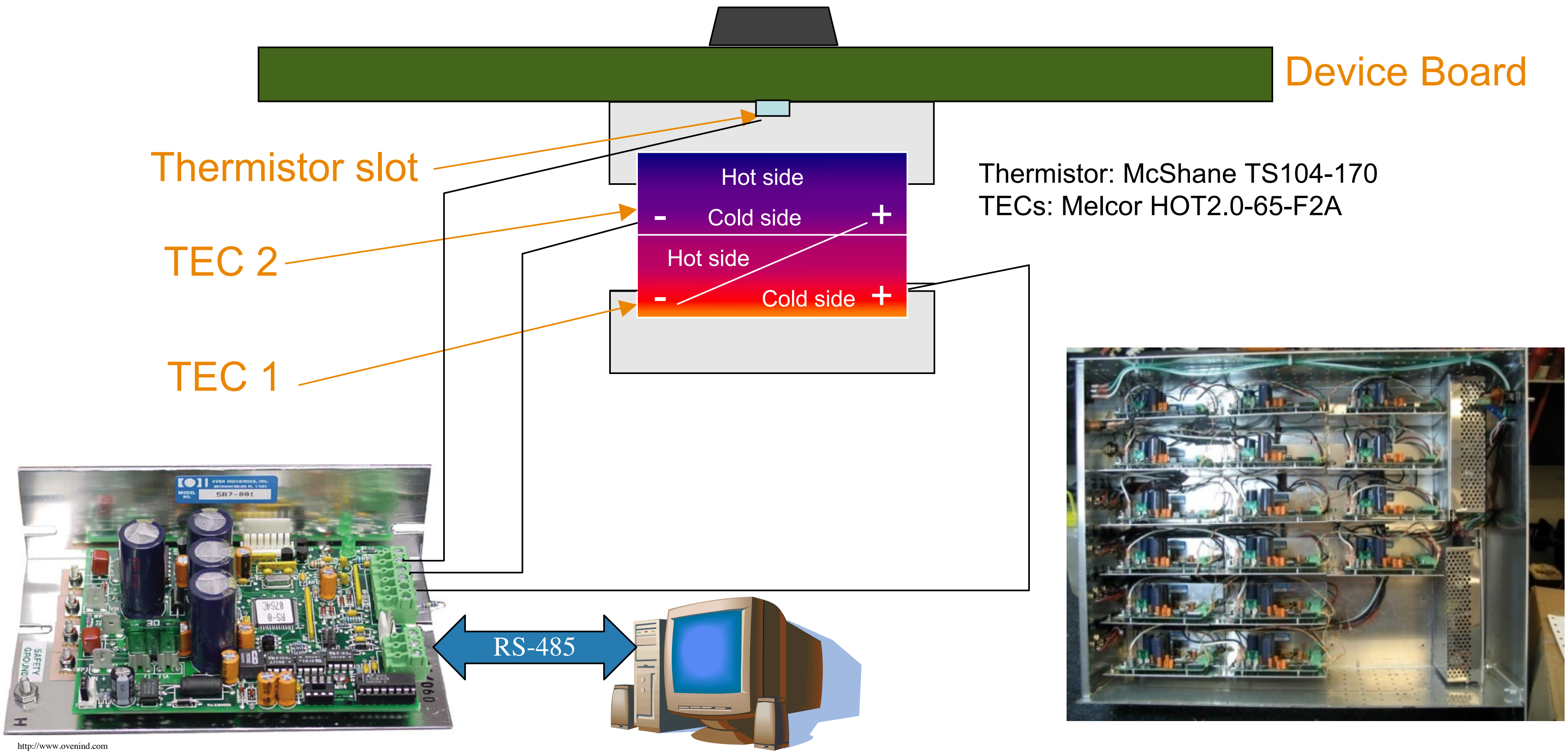
Electrical Characterization Thrust



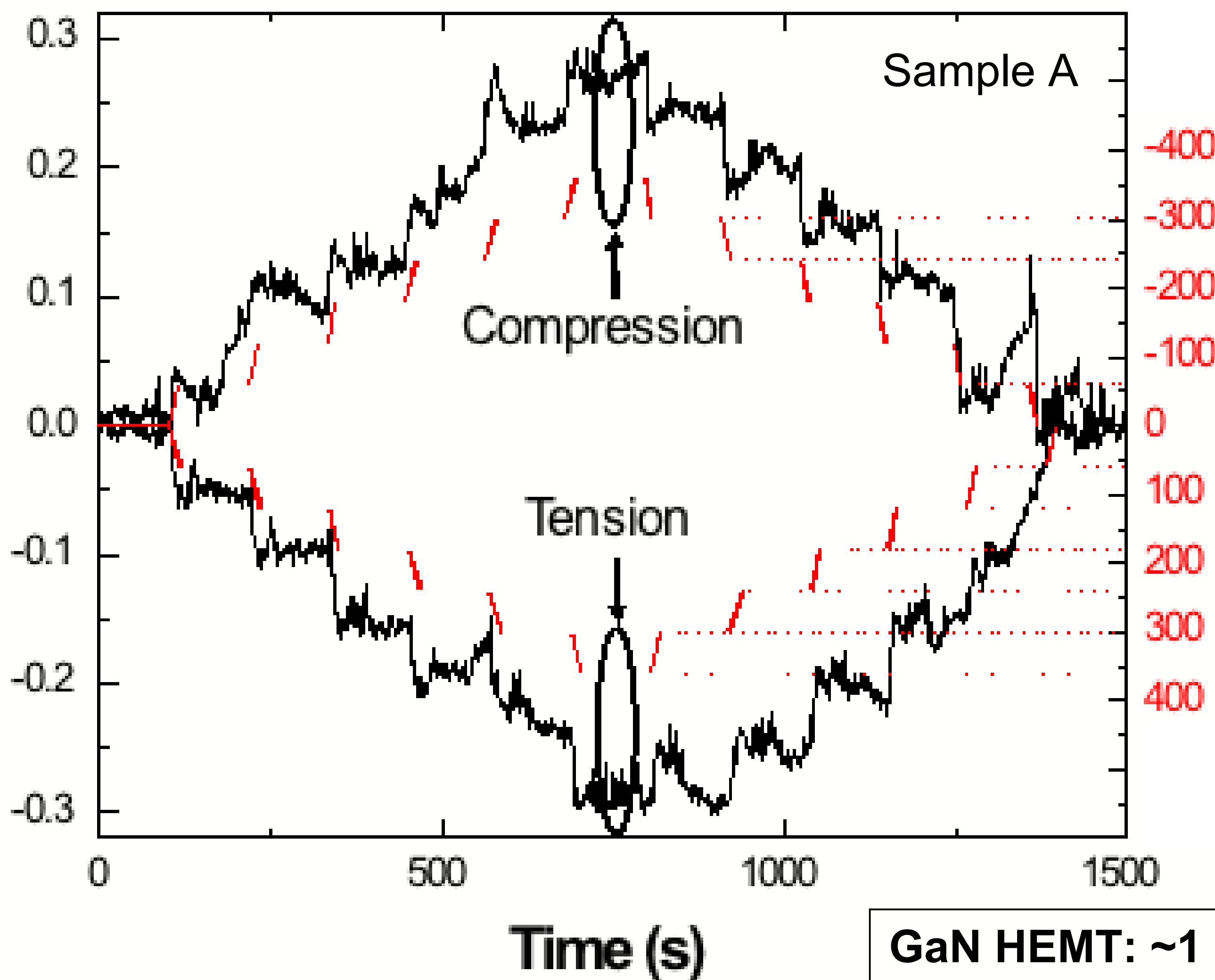
Testing System Turnkey vs. In-house

	Turnkey		In-house
Timeline	Purchase lead time		On-going
System	Proven		Custom design
Objective	Determine Lifetimes		Research Determine failure mechanisms
Test Types	Industry standards		Flexible
DC Drain Gate	0-100V, up to 4A, 400W max ±18.5V, up to 200mA		0-60V, up to 6A, 300W max ±10V, up to 20mA
RF	600MHz-3 GHz 2-18 GHz 58-60 GHz	900MHz-10GHz 36-40 GHz 76-78 GHz	1.8-2.2 GHz expandable with additional hardware
Temperature	50° to 250° C		25° to 250° C
Optical	NA		Research with wavelength and intensity
Thermal Imaging	NA		IR, Micro Ramon additional hardware
Pulse	1-100kHz		Up to 80MHz
Data Storage	Independent test files		SQL database

UF Semiconductor Reliability System



Temperature Measurement and Control



GaN HEMT: ~1 %/GPa
Si nMOS: ~31 %/GPa

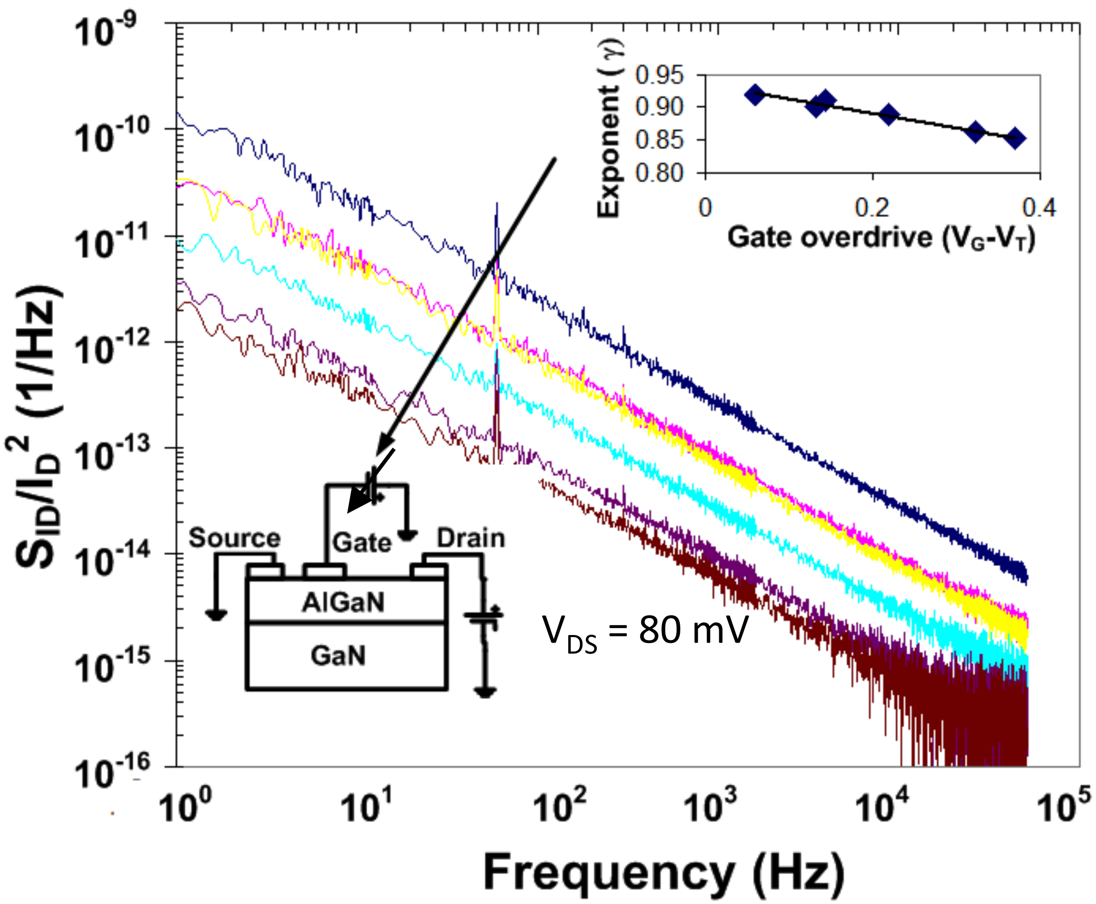
GaN HEMT Piezoresistance

Wide range of published gauge factors (GF)

Reference	GF	ΔR/R	ε (%)	σ (MPa)	Method of Stressing
This work	**-2.6**	**0.3%**	**0.114**	**360**	**4-point bending**
[1]	-4	0.14%	.03	95	3-point bending
[2]	-42	0.2%	.005	15	3-point bending
[3]	-75	3.5%	.04	126	3-point bending
[4]	-90	15%	0.167	525	Cantilever
[5]	-350	5%	.0143	45	Lever-Mass
[6]	-1,259	1.7%	1.35×10^{-4}	0.42	Cantilever
[7]	-38,889	15%	3.85×10^{-4}	1.2	Circular Membrane

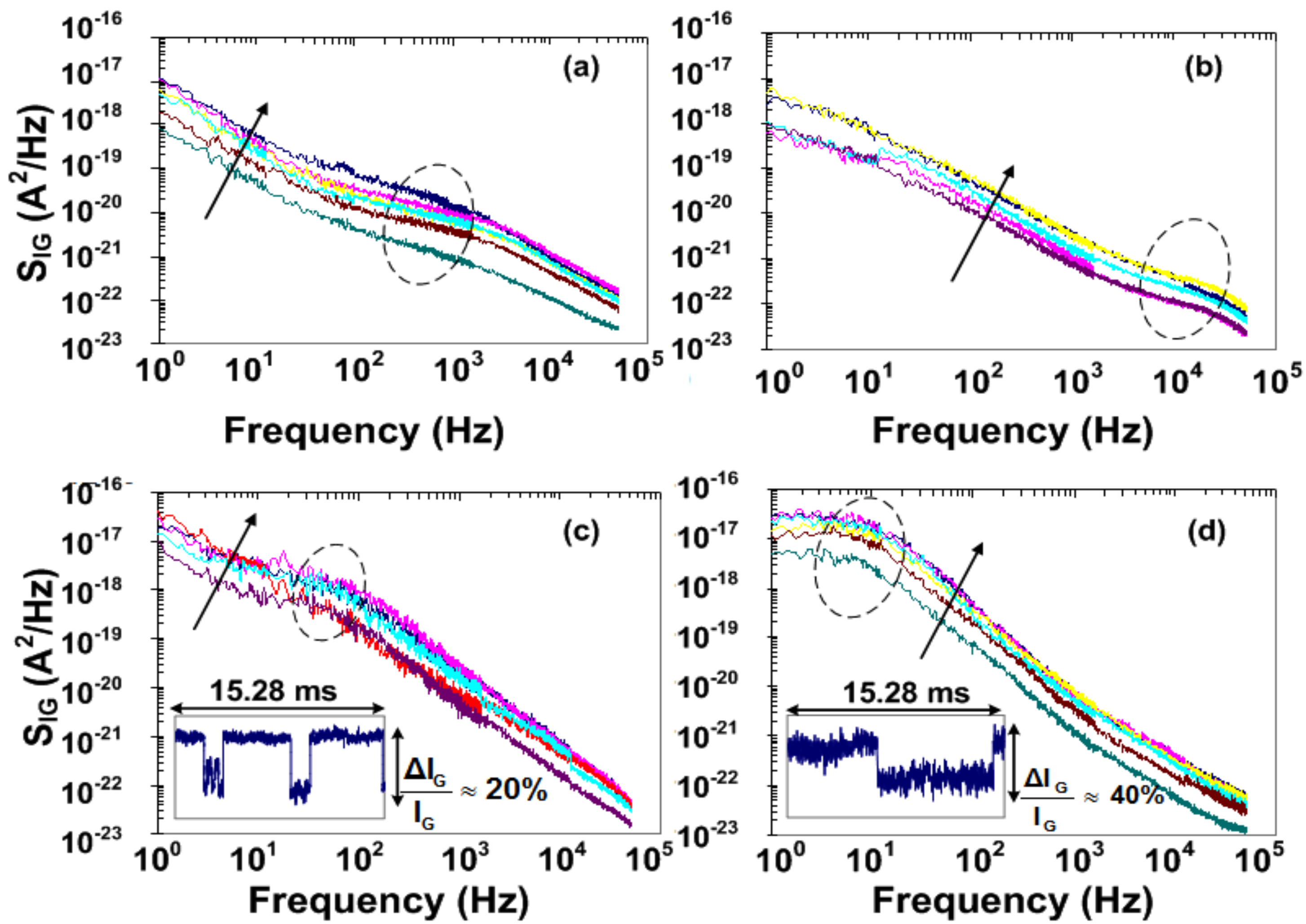
[1] R. Gaska, et al, *APL*vol. 72, pp. 64-66, 1998.
[2] M. Eickhoff, et al, JAP, vol. 90, 3383-3386, 2001.
[3] C. T. Chang, et al, *IEEE Electron Device Letters,* vol. 30, pp. 213-2152009.
[4] T. Zimmermann, et al, *IEE Electron Device Letters,* vol. 27, pp. 309-312, 2006.
[5] O. Yilmazoglu, K. et al, *EICE Trans Electron,* vol. E89-C, pp. 1037-1041, 2006
[6] B. S. Kang, et al, *APL,* vol. 83, 4845-4847, 2003.
[7] B. S. Kang, et al, APL, vol. 85, pp. 2962-2964, 2004.

Stable drain noise characteristics

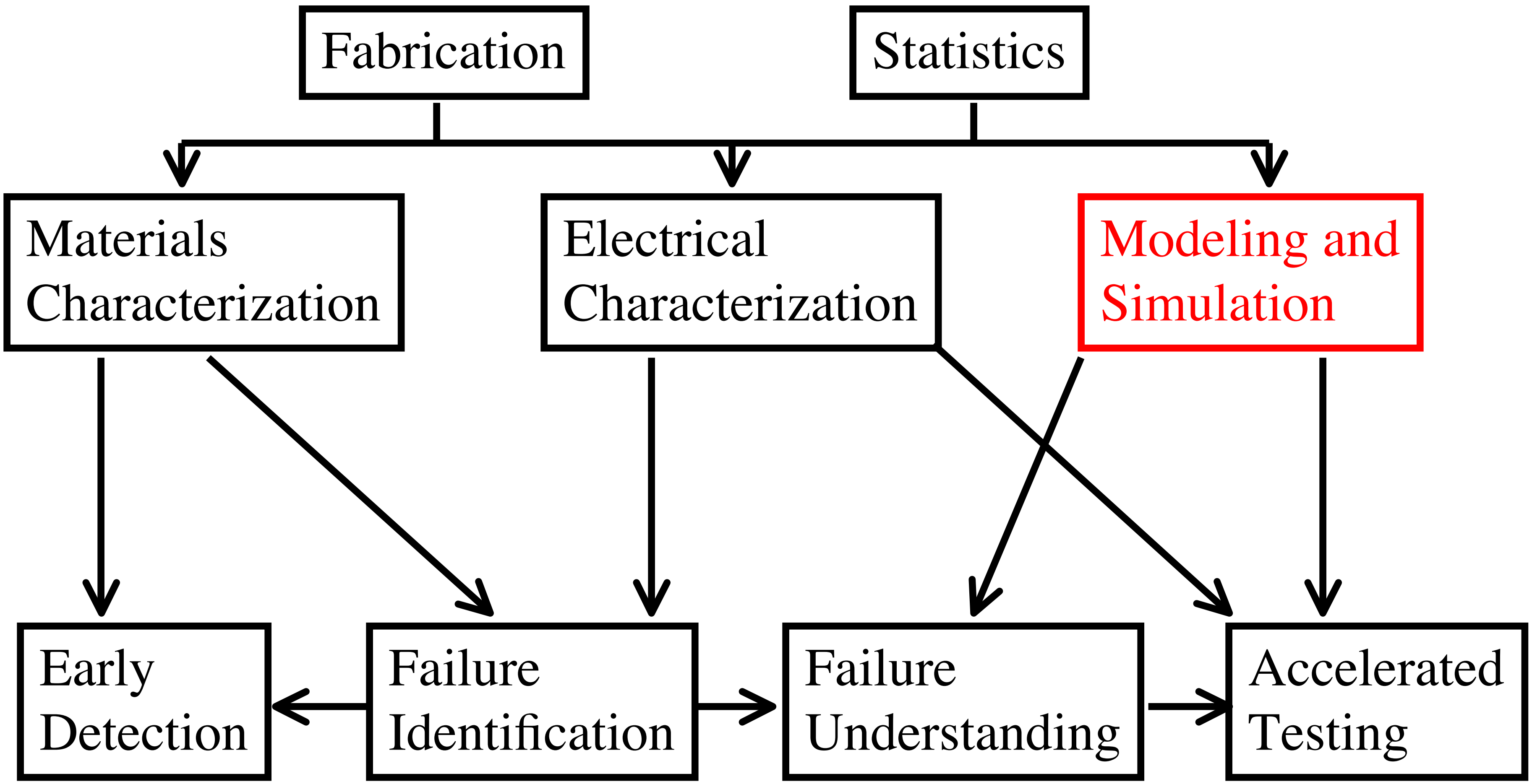


- Drain noise measured as a function of V_{GS} for constant low V_{DS}
- Frequency exponent (γ) is a inverse function of the gate overdrive voltage.
- Indicator of non-uniform trap distribution. High band-bending in AlGaN barrier creates a trap distribution skewed towards the interface leading to high frequency traps.
- No distinct generation-recombination components at room temperature.

Gate noise instability



Simulation Thrust



2DEG Density Calculation Procedure

AlGaN

Build in P_{SP} + $P_{PE,lattice}$

Additional strain from mechanical stress → **$P_{PE,\ mechanical}$**

Piezoelectric Constant → **$P_{PE,\ mechanical}$**

GaN

Build in P_{SP}

Additional strain from mechanical stress → **$P_{PE,\ mechanical}$**

Piezoelectric Constant → **$P_{PE,\ mechanical}$**

↓

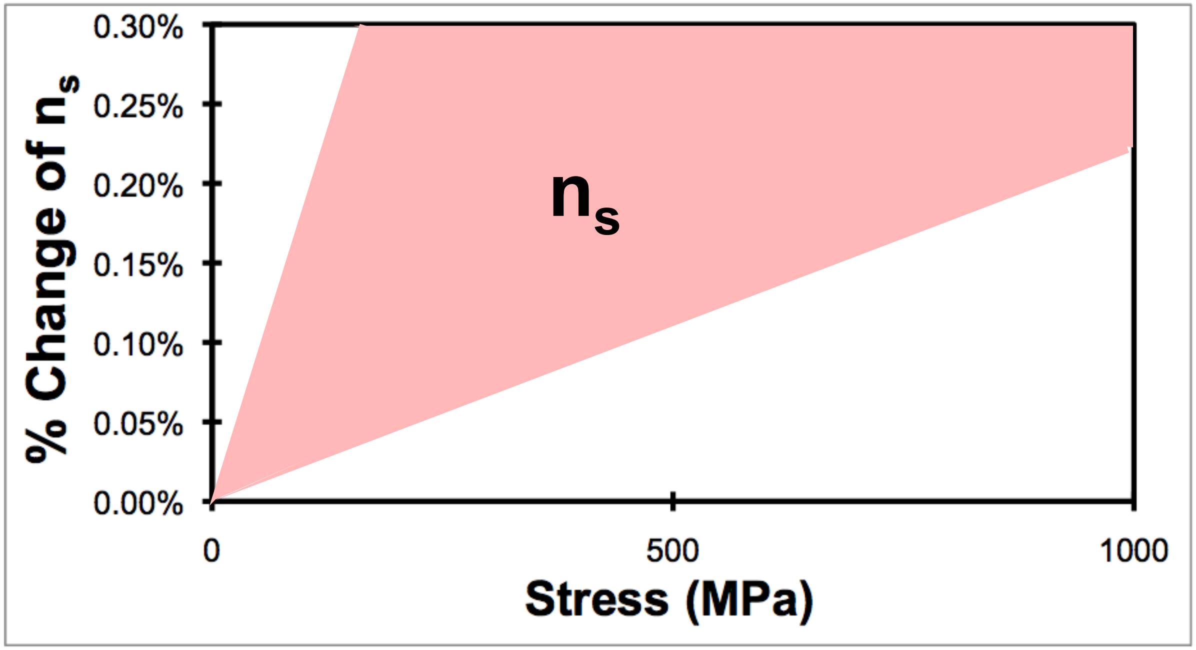
$$P_{total} = P_{SP}(AlGaN) + P_{PE,lattice}(AlGaN) + P_{PE,mech}(AlGaN) - P_{SP}(GaN) - P_{PE,mech}(GaN)$$

↓

2DEG Density: $$n_s(x) = \frac{P_{total}}{e} - \left(\frac{\varepsilon_0 \varepsilon(x)}{de^2}\right)\left[e\varphi_b(x) + E_F(x) - \Delta E_C(x)\right]$$

[Ref:JAP, vol.85, pp.3222]

Strain-Varied 2DEG Density

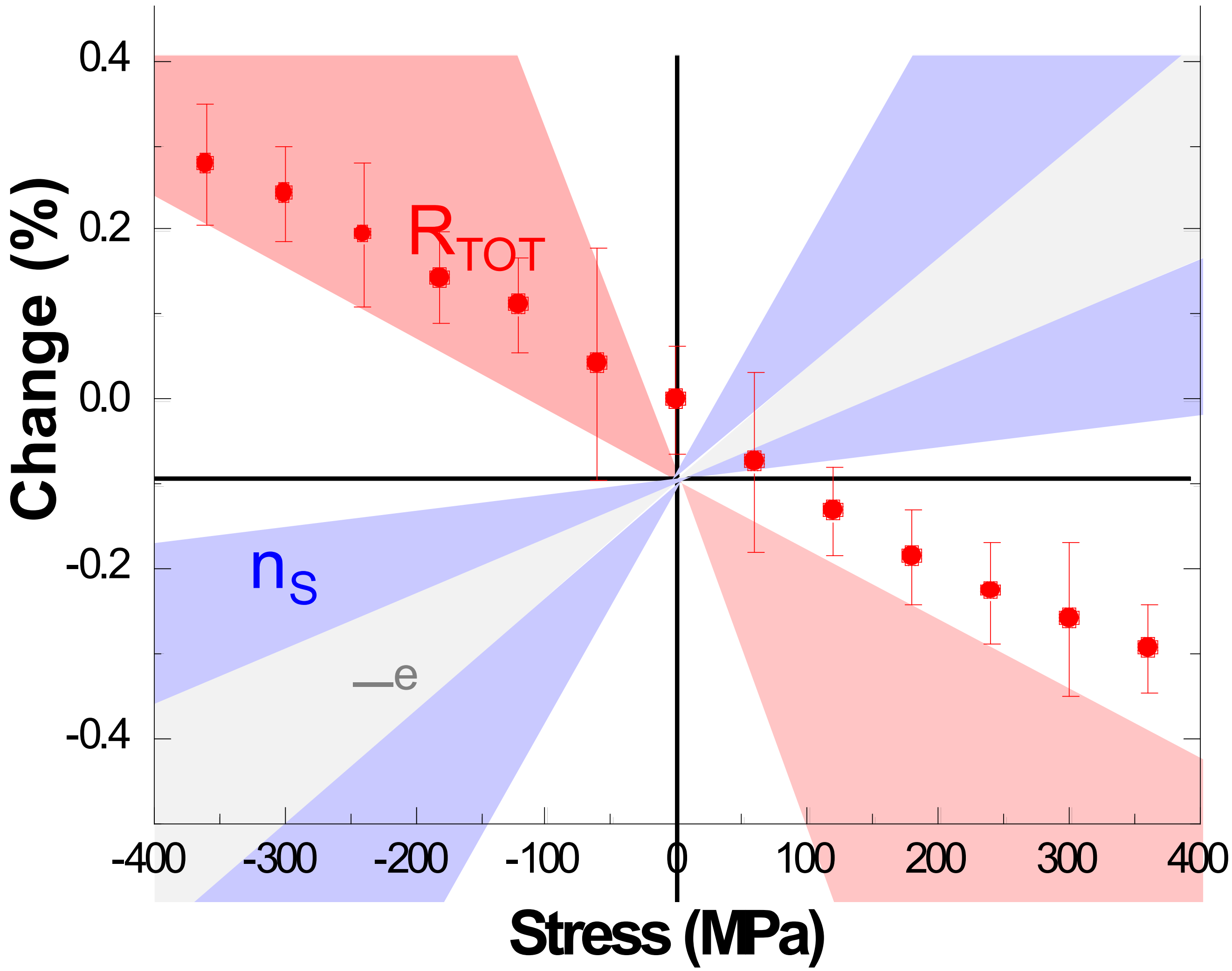


$$n_s(x) = \frac{+P^{int}(x)}{e} - \left(\frac{å_0 å(x)}{de^2}\right)\left[eö_b(x) + E_F(x) - ÄE_C(x)\right]$$

Assumed independent of stress:
- ϕ_b since ΔP^{int} is small
- ΔE_C since only 26% Al in AlGaN
- ε and E_F since no change in Si and no papers reporting change for GaN

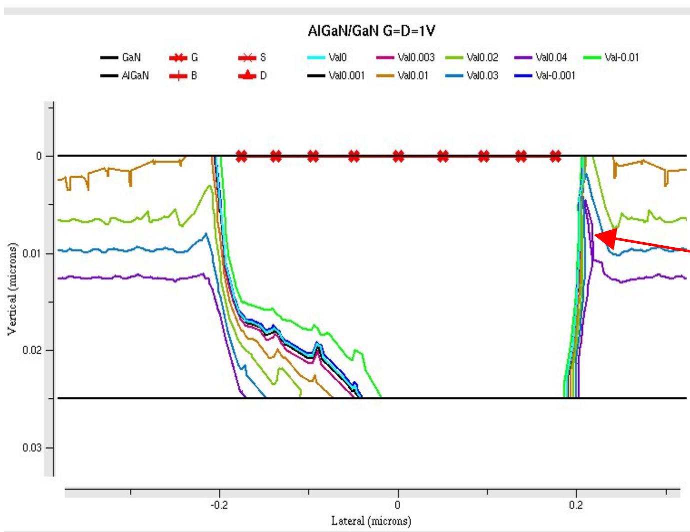
- Small changes observed in n_s (0.28%/GPa) since external stress creates offsetting piezoelectric polarizations

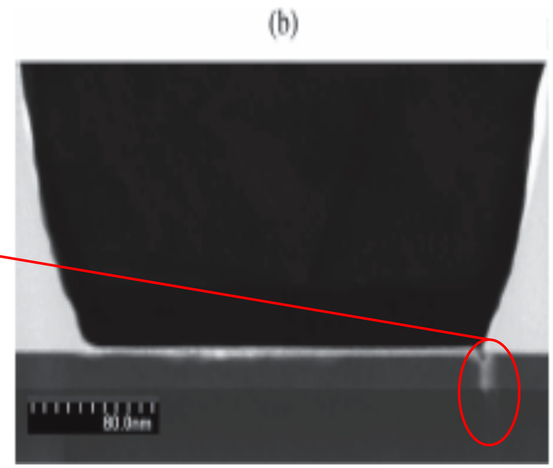
Simulation vs. Experiment



Inverse Piezoelectric Effect Calculation

- Mechanical Simulation with InversePiezo and Lattice Mismatch Terms
- Low voltage applied
- Sharp bunching of strain from inversepizeo terms near drain edge





Temperature Models

All temperature dependence has been implemented

Thermal transport equations (Wachutka, IEEE Trans. Comp. Aided Des., **9**, no. 11, 1990)

$$c \cdot (\partial T/\partial t) = \mathrm{div}\,(\kappa \vec{\nabla} T) + H$$

$\varkappa \equiv$ thermal conductivity

$c \equiv$ lattice heat capacity

	GaN	AlGaN
$\varkappa$ (W/cm•°K)	2.67	0.33
c (J/°K•cm3)	1.395	1.395

H = Heat Generation rate, several interpretations are in the literature

$$H = q \cdot \mathrm{div}\,(\phi_n \vec{j}_n - \phi_p \vec{j}_p).$$

ϕ_n ,$\phi_p \equiv$quasi-fermi levels of e, h

because hole concentration is negligible, simplified to

$$\vec{j}_n = \mu_n \cdot n \cdot \vec{\nabla}\phi_n$$

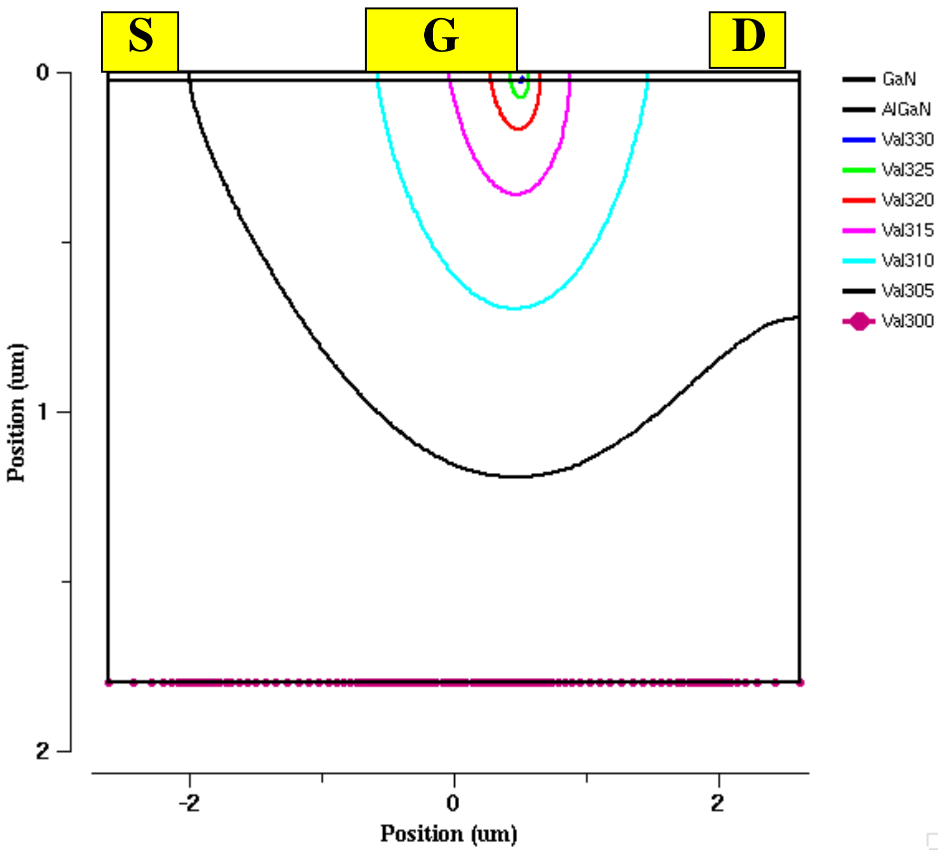
$$H = q \cdot \mathrm{div}\,(\phi_n \vec{j}_n - \phi_p \vec{j}_p).$$

$$\vec{j}_p = -\mu_p \cdot p \cdot \vec{\nabla}\phi_p$$

Fixed temperature boundary condition applied to bulk contact:

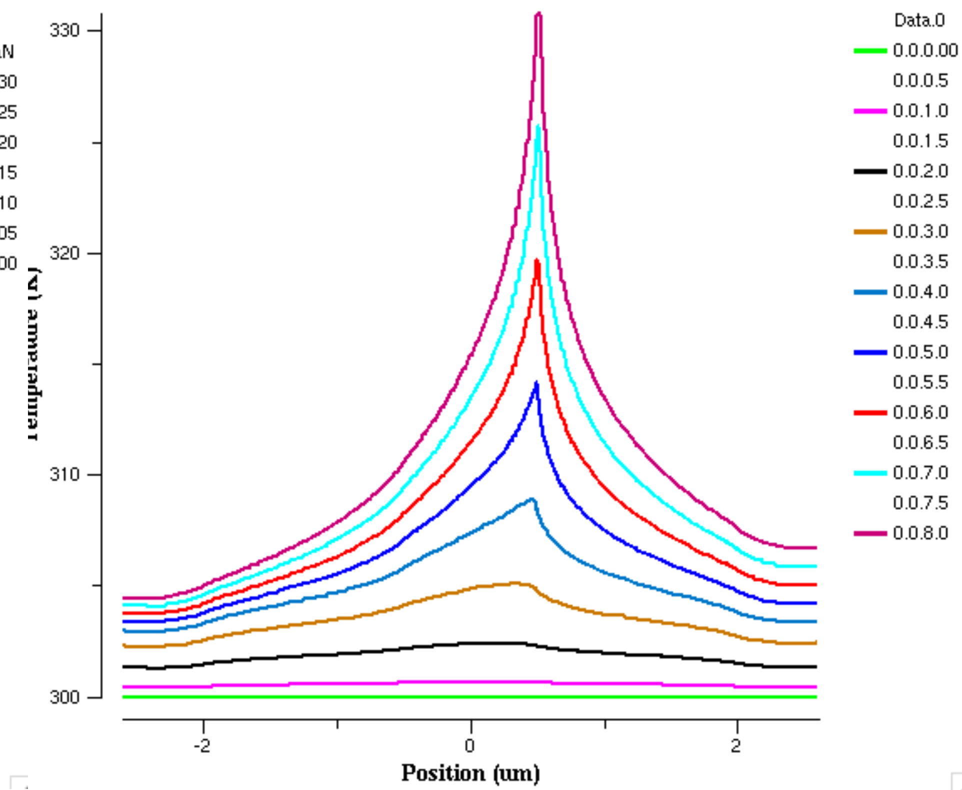
$T_{bulk\_contact}$=300 (K)

Temperature Profiles



Contour plot of temperature

V_G=0 V V_D=8 V



Temperature across device through AlGaN increasing bias

V_G=0 V V_D=0 V to 8 V

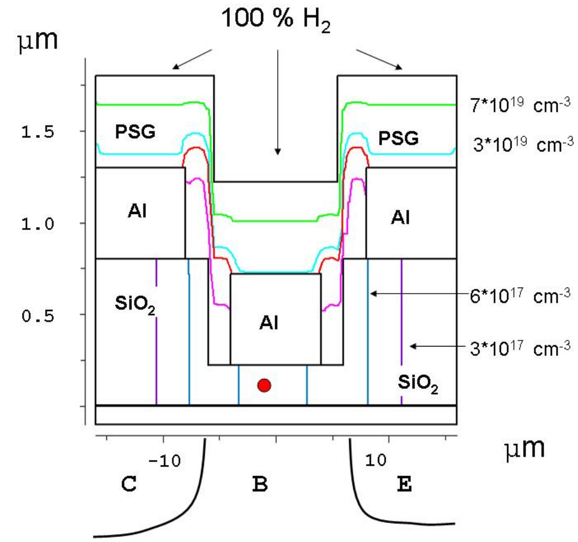
UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Michelle Griglione, Poster

A 21st Century Approach to Reliability

Collaborations w/ DRIFT and Others

- Vanderbilt
  - Surface Degradation
  - Hydrogen Behavior During Device Operation
  - Existing Collaboration on Radiation Effects
- MIT
  - Overlapping Interest in Stress
  - Share data and models
- Georgia Tech
  - Sharing devices, data



TNS, TBP

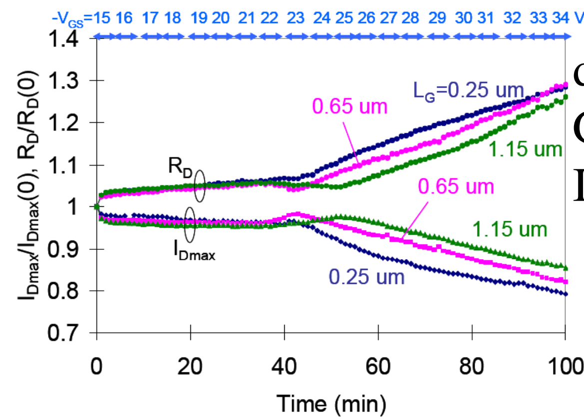
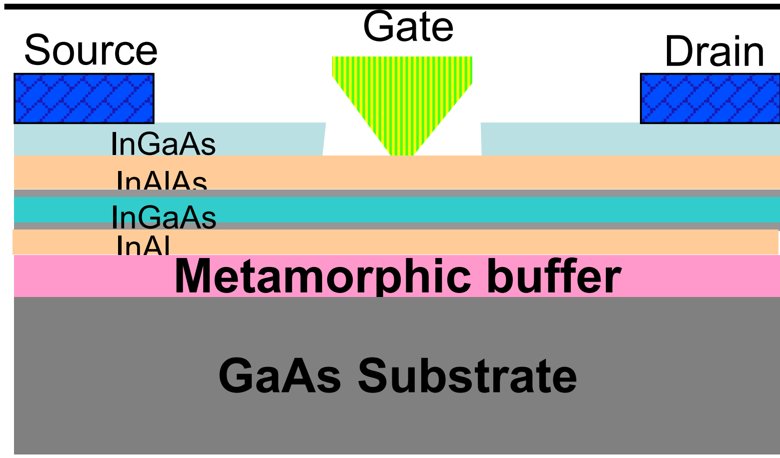
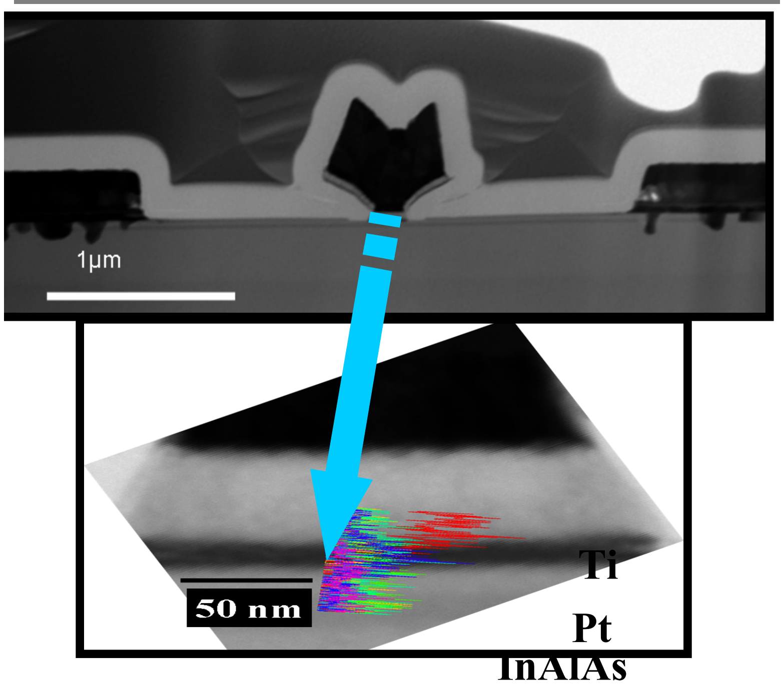


Fig. 11. Gate length dependence of degradation. Different gate length devices (type A1, L_G=0.25, 0.65, and 1.15 um) are stressed at V_{DS}=0 and V_{GS}=-15~-34 V (-1 V step, 5 min/step). The threshold of the degradation increases with L_G.

del Alamo Group, 2006 IEDM

Degradation Mechanisms in InAlAs/InGaAs MHEMTs with 150 nm Mushroom Gates



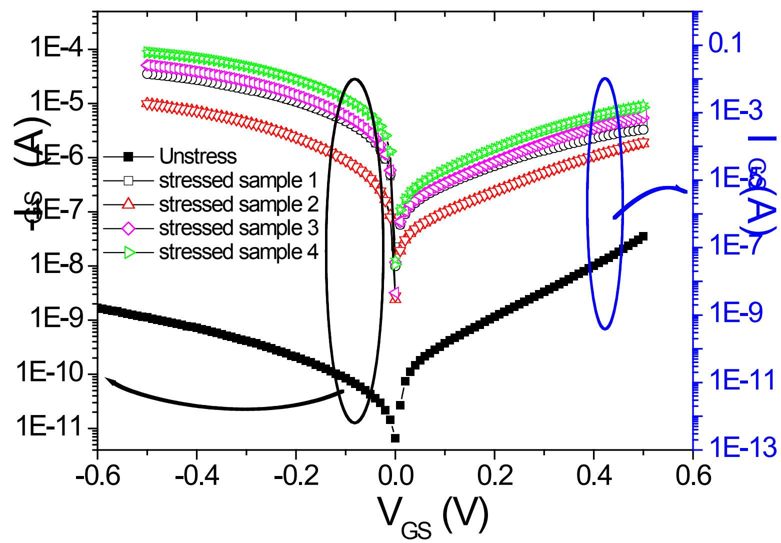


Degradation mechanisms of InAlAs/InGaAs pHEMTs reported include:

- Ohmic Contact
- Layer Structure
- Fluorine Contamination
- Bias Dependence
- Gate Recess Depth
- Gate Metal Sinking

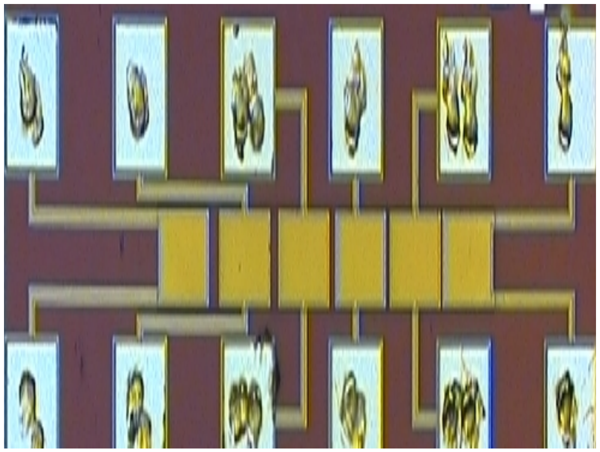
Private communications indicate that ALL InAlAs/InGaAs HEMTs suffer from an initial decrease in IDSS - this is accommodated by a burn-in to get the devices to a new equilibrium.

After DC stress, the Pt from the mushroom gate diffused into InAlAs layer, confirmed with TEM images and EDS analysis.

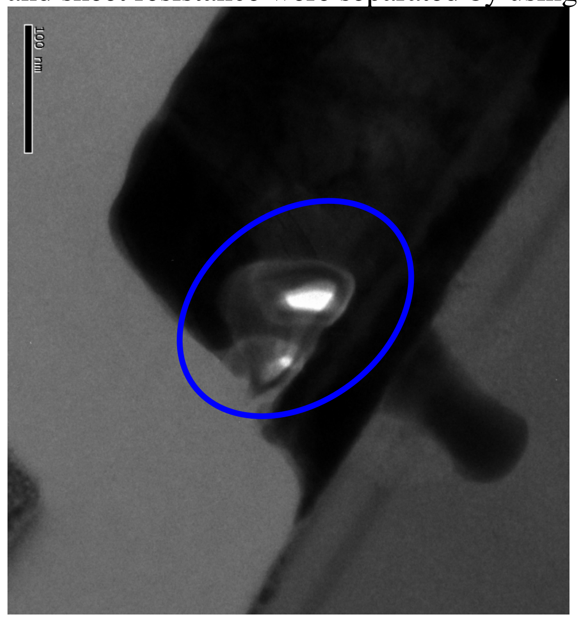


Degradation Mechanisms in InAlAs/InGaAs MHEMTs with 150 nm Mushroom Gates

Device stressed at higher current density at 10^5 A/cm2 exhibited electromigration induced void on the edge of the Ohmic metal contact pads. The effects of field, and changes in contact and sheet resistance were separated by using TLM patterns in addition to the actual devices.



TLM pattern with pad gap 3 μm, 6 μm, 9 μm, 12 μm and 15 μm.



The increases of the TLM resistance during DC stress and thermal storage resulted from different mechanisms
-The Rc deterioration was dominant in the thermal stoage test and the Rs increase was observed in the DC stress.
-Metal spike formation and ohmic metal diffusion are observed during the thermal storage.
The DC stress would be further conducted (different stress conditions) to investigate the device electrical performance including saturation current, gate modulation behavior, threshold voltage, leakage,gate lag..etc in order to compare the degradation behavior.

Conclusions

- Science Based Program
- Directed at:
  - Improved Testing Methodology
  - Greater Understanding of Failures
  - Failure Prevention Strategies
- Strong Collaborations
  - Industry
  - University Partnership